A novel magnetizer for 2D broadband characterization of steel sheets and soft magnetic composites

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1. Introduction

Two-dimensional (2D) characterization of soft magnets is generally performed using either a vertical-horizontal double-yoke magnetizers and square samples [1][2] or a three-phase magnetizer with circular/hexagonal samples [3][4]. While the latter approach is known to ensure better field homogeneity, the test frequency at technical inductions can barely attain, in all cases, a few hundred Hz. On the other hand, increasing applications of high-speed electrical machines call for 2D characterization at much higher frequencies. To this end, a novel experimental setup based on a three-phase yoke has been especially designed, exploiting 3D finite elements (FEM) calculations, and realized, permitting one to measure magnetization curve and losses in soft magnetic laminations and soft magnetic composites under alternating and circular induction up to about 5 kHz. In this paper we provide a full description of such a setup and we provide a few significant examples of loss measurements in 0.20 mm thick Fe-Si and $Fe_{50}Co_{50}$ laminations. These measurements bring to light the role of skin effect under one- and two-dimensional excitation.

2. Design of the experimental setup

Design constraints

- A minimum objective is to reach a peak polarization J_p = 1.5 T at a frequency f = 1 kHz in a d = 0.2 mm thick Fe-Si sample.
- Each phase of the three phase magnetizer is supplied by a 5 kVA CROWN 5000VZ linear amplifier, whose maximum peak voltage is $V_{p,MAX}$ = 150 V, and maximum peak current is $I_{p,MAX}$ = 40 A.

Optimization of the magnetizer geometry

The following parameters are imposed at start:

- Circular sample of diameter D = 80 mm, sufficient to guarantee an adequately wide central measuring region of uniform induction. A minimum airgap a = 1 mm ensures reasonably low demagnetizing fields.
- Three pole pairs with three slots per pole (Fig. 1).
- A yoke made of standard 0.35 mm thick Fe-Si stacked laminations.

Four parameters are optimized: the slot depth t_S, the slot width w_S, the yoke back-core width t_Y, and the active axial height of the stacked magnetizer T (Fig. 1). Finally, optimal number of copper turns n_s per slot is envisaged. t_S (20 mm) and w_S (5 mm) are chosen under the constraint of maximum magnetizing current density of 5 A/mm^2. t_Y is set to 25 mm and the ratio T/d is obtained by 3D magnetostatic finite element (FEM) modelling (Fig. 1). The total peak current in a coil n_sI_p and the peak flux per turn φ_p/n_s required to reach a rotating peak induction B_p = 1.5 T in the disk sample is shown in Fig. 2 versus the ratio T/d. The apparent power, proportional to the product φ_pI_p, is found to be minimum for $T/d \cong 75$, corresponding to T = 15 mm. This gives φ_p/n_s = 2 mWb and n_sI_p =

100 A. With n_S = 10, the required peak current is I_p = 10 A, corresponding to an inductive voltage V_p = 127 V, safely provided by the adopted power amplifiers.

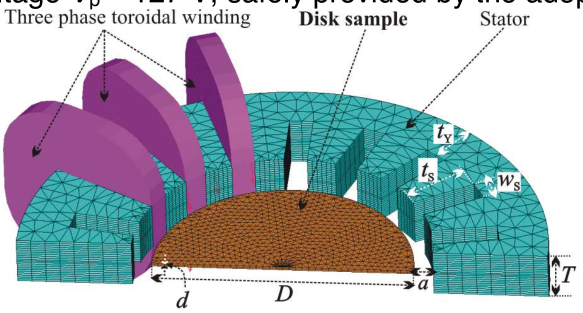

Fig. 1. 3D finite element model of the measurement setup, and the involved geometrical parameters.

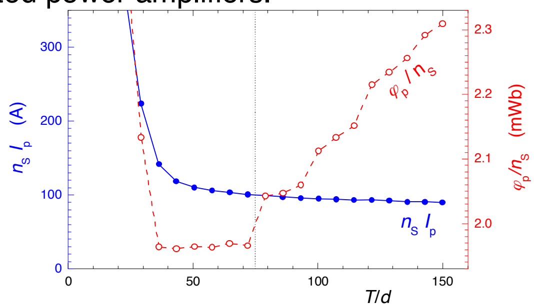

Fig. 2. Peak current in a coil $n_S I_p$, and resulting peak flux per turn φ_p/n_S corresponding to the rotating peak induction B_p=1.5 T.

Measurements

Test measurements are performed with the fieldmetric method [4], upon a 20 mm squared region, where the 3D FEM analysis shows good field homogeneity. Fe-Si and Fe-Co sheets have been characterized, under alternating and rotating field, up to J_p = 1.55 T (f_{max} = 2 kHz) and J_p = 2.1 T (f_{max} = 5 kHz), respectively. An example of loss results in the Fe-Co sheet is given in Fig. 3. The observed strong deviation of W_{diff}=W_{hyst}+W_{exc} from an $f^{1/2}$ dependence, both under alternating and rotating induction (Fig. 3b), points to the appearance of the skin effect in the upper frequency range.

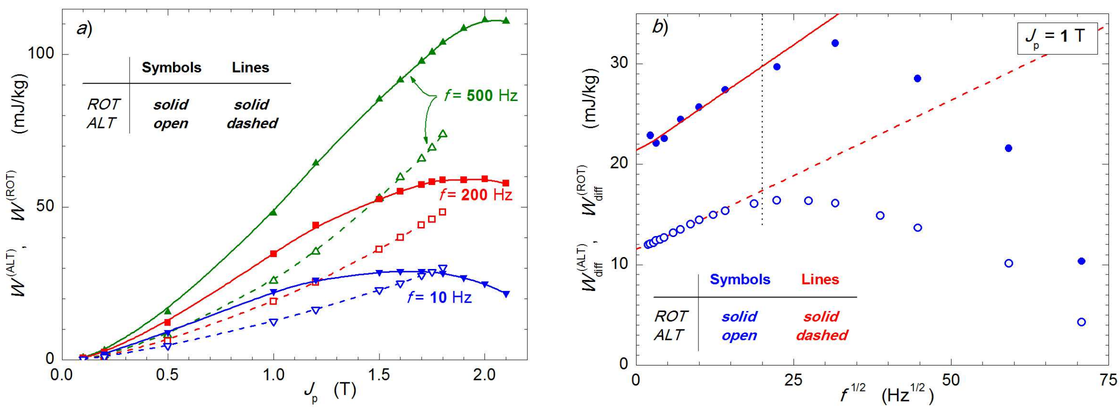

Fig. 3. a) Alternating and rotational energy loss measured in 0.20 mm thick Fe-Co laminations (a) and the associated dependence of the sum of the hysteresis and excess loss components versus $f^{1/2}$ (b). Strong non-linear behaviour of this quantity correlates with the appearance of the skin-effect.

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